PWSCC in Tube Expansion Zone - An Overview

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1 INTRODUCTION

This paper presents an overview of the problem which affects most of the PWR Steam Generators (SG) with a tube bundle in Inconel 600 alloy : Primary Water Stress Corrosion Cracking (PWSCC) in the Expansion Zone (EZ) and, more specifically, the Roll Transition (RT) of tubes mechanically expanded in the tube sheet.

2 PROBLEM DESCRIPTION

2.1 Primary water stress corrosion cracking of Inconel 600

Stress Corrosion Cracking (SCC) is known to result from the conjunction of three factors

- a susceptible material.
- an aggressive environment.
- a high stress level.

For Primary Water SCC (PWSCC) of Inconel 600 alloy

- the material is most susceptible to intergranular SCC under its usual "Mill Annealed" (MA) condition. Susceptibility may be reduced by a subsequent heat treatment achieving carbides precipitation at the grain boundaries. Depending on the temperature and duration of the treatment the structure may be left in a "sensitized" condition (dechromization of the grain boundaries) or reach an "optimum" condition (chromium rehomogenization, as typically obtained by a Thermal Treatment - TT- of 15 h at 715°C).

- the aggressive environment is basically pure water. The chemical additives (H_2 , B, Li,...) and impurities do not have an important effect.

A major influence is exercised by temperature, in accordance with an Arrhenius law ; i.e. the time to cracking initiation (incubation time) is proportional to $\exp(E/kT)$, where T is the absolute temperature and E is an activation energy.

- the tensile stress level required is relatively high (typically at or above the yield stress) ; this explains why PWSCC occurs at particular locations with high stress concentration factors or built in residual stresses. The most frequent occurrence, likely to affect all tubes of a SG, is the expanded section within the tube sheet. The extent of damage is a function of the residual stresses induced by the expansion process and is maximal for mechanical rolling.

2.2 Cracking phenomenology and morphology

Tube Mechanical expansion is obtained by successive roll steps, about 25 mm long, which may either be limited to the lower end of the tube sheet hole ("part depth" rolling) or be extended over the full thickness of the tube sheet ("full depth" rolling); a last step of controlled expansion above the top of the tube sheet (fixed diametral increase, called "kiss roll") may also be present (mostly in European plants). Typical configurations are illustrated by Fig. 1.

Mechanical roll expansion is a technological process which is far from achieving the ideal expected condition of straight profile and uniform compressive stress all along the tube sheet contact area.

Cracks initiated within the tube sheet do not usually lead to a safety (tube rupture) or operational (tube leakage) concern. This is no more so for cracks located at or above the top of the tube sheet. Unfortunately PWSCC may occur at any of the normal roll transitions (from fully expanded to unexpanded) even if they are perfectly within tolerance and whether they are provided or not with kiss rolls.

The overview will further focus on this roll transition area.

Cracking is usually well distributed over the entire surface of the tube sheet hot leg side, with occasional clusters of variable pattern.

Cracks initiate at the tube ID at the location of maximum stress level (in the range of 400 MPa when combining the residual and service stresses) and propagate in an intergranular mode.

The total tensile stress is usually somewhat larger in the hoop than in the axial direction. Thus axial cracks are the most common appearance of PWSCC in roll transitions.

Axial cracks propagate very rapidly through the wall thickness, so that most of the cracks appear (close to) through-wall when first detected by the most sensitive inspection methods (ECT-RPC); they further extend in length and may grow out of the roll transition area.

The axial cracks are usually multiple in the same tube cross section; the number of cracks increases with time and may range from a few up to some twenty. There is but one known case (replaced SG of Dampierre 1) with a superimposed pattern of numerous (up to several hundreds) short and shallow microcracks in a band structure.

In some cases, the cracks are somewhat inclined (10 to 30 degrees) with respect to the axial direction and, more exceptionnally, they may turn circumferentially or develop significant circumferential branching; the latter are typically associated with major manufacturing defects like overrolling or severely out of tolerance tube sheet holes (both cases resulting in "rolling in the air").

Because the total stress level remains comparable in the two orthogonal principal directions there are cases where the axial stress prevails over the hoop stress, thus leading to initiation of circumferential cracks, either isolated or in combination with axial cracks (mixed mode cracking). Moreover a relatively large and totally unexpected circumferential problem has affected Inconel 600 TT (thought to have but a low susceptibility to PWSCC) in several recently commissioned French SG. The problem resulted from severe tube denting at the top of the tube sheet caused by swelling of oxydized grit deposits (probably from some grit blast cleaning performed in the SG secondary system during site installation).

Circumferential cracking does not propagate as readily through-wall as mentioned for the axial case. Several cases have been observed of very long cracks (up to the full circumference) with no or very limited TWD extent.

2.3 Characterization methods

2.3.1 Inservice inspection

Inservice Inspection (ISI) requirements are enforced by the safety and regulatory body of the various countries operating PWR's. With some variations, they imply a sampling plan of the tube bundle and the use of an "all purpose" Eddy Current Testing (ECT) methodology with a Bobbin Coil (BC) inspection probe.

Because the PWSCC defects are very tight, the ECT-BC technique has but limited sensitivity and poor sizing capability.

The ECT Rotating Pancake Coil (RPC) technique has a far superior detection sensitivity and an excellent sizing (in length) capability for axial cracks.

The reliable detection threshold is about 3 mm in length ; however the best available methods would detect most of the cracks 2 mm long and even a substantial proportion of those 1 mm long ; the sizing accuracy varies with each particular equipment but may come down to a range of about ± 1 mm. For circumferential cracking the detection threshold is at least doubled for isolated cracks and is still much worse in the presence of axial cracks (mixed mode cracking).

This has promoted the development of alternative Ultrasonic Testing (UT) techniques (of either the "rotating probe" or "rotating mirror" types) which are able to differentiate the axial and circumferential components of a complex cracking pattern with a detection sensitivity of about 2 mm and a sizing accuracy of about 1 mm.

Once roll transition PWSCC has been detected (by ECT-BC) in a plant, the RPC technique is required for complementary expertise. There is presently a move towards 100 % inspection (all tube roll transitions) by ECT-RPC technique. Belgium was the first country take the move since 1988 ; several european countries are presently following the same policy, with a similar trend in the USA.

Implementation of the ECT-RPC technique was initially slowed down by the economical concern raised by a lengthy inspection process impacting on the plant outage duration. This promoted development of impressive technological improvements.

For instance, LABORELEC developed a sophisticated data acquisition and analysis system coupled to a fast robust positionning device. Each inspection task is achieved automatically using microprocessor control and high performance desktop computers, with nearly no human interventions except for the maintenance and the final signal interpretation. Fig. 2 illustrates a typical print-out of "on line" computer diagnostics. Field implementation of this technology allowed, since 1988, inspection of all tubes (for a length of 150 mm with a helical pitch of 1 mm) of all SG of a plant in a time of 2 1/2 days per SG, including the equipment installation and removal and the issuance of a preliminary inspection report.

Because of the limited occurrence of circumferential cracking, the UT technology has not yet taken a similar extent of field implementation. Moreover the technique is reputedly much slower than ECT-RPC. Here again spectacular improvements have been made and LABORELEC has demonstrated, by UT field inspection of several hundred tubes, that the examination time can be brought down to a mere 90 s/tube (inspected length of 60 mm with a helical pitch of 0.7 mm).

2.3.2 Laboratory expertise

Despite the high performance of ISI, laboratory expertise of representative tubes pulled from affected SG remains a key requirement for

- defect characterization,
- correlation to tube and environment features,
- verification of the efficiency of repair techniques.

Another purpose of tube pull expertise is to allow calibration of the ISI technique in order to achieve the desirable level of reliability in signal interpretation and of accuracy in the defect sizing.

3 PREVENTIVE METHODS

Preventive methods are acting on any of the three contributing factors to PWSCC, in order to move away from the detrimental combination.

3.1 Decreasing the material susceptibility

For Inconel 600 in the MA condition, a metallurgical improvement can be achieved by a site thermal treatment. The optimum treatment above 700°C (cf. § 2.1) can only be applied to the tube free span. However for both full depth and part depth rolled plants, there is an alternate possibility of heating the entire tube sheet at a temperature not exceeding 620°C ; for durations in the range of 100 hours this is sufficient to get sensitization and a corresponding reduction of susceptibility to PWSCC, while leaving the structure prone to other type of IGSCC in presence of some contaminated environments. An additional advantage from the global heat treatment is a partial relaxation of the residual stresses.

While this method was fully investigated in Belgium and shown to provide a valuable and workable technological solution, it has never been implemented.

3.2 Decreasing the stress level

Tensile stress reduction has mainly been addressed by the peening techniques which are used to induce a shallow compressive layer (about 0.1 mm deep) at the tube inside surface.

Two techniques have been developed and field implemented

- shot-peening uses the impact of air borne free particles of metallic alloy
- roto-peening uses the hammering of carbide particles attached to the flexible "flappers" of an eccentric rotating shaft.

The peening techniques have been extensively applied to the hot leg side of most SG with Inconel 600 MA in Europe and USA ; because of a slightly better efficiency (from laboratory tests) and easier technological implementation, shot-peening was by far more frequent than roto-peening. Shot-peening was also applied to the cold leg side of a few european plants and is further considered for the hot leg side of plants with Inconel 600 TT.

The test programs had indeed evidenced a very high efficiency of the peening process towards crack initiation, and had induced to believe that already initiated cracks would not propagate in length, though they could become through wall.

The RPC inspections, performed over a period of 5 cycles after peening, show a more pessimistic picture :

- the previously detected cracks are observed to steadily increase in length, by an average value of about 1 mm/cycle;
- the number of cracked tubes increases by an average value in the range of 5

to 10 %/cycle, the percentage being taken with respect to the total tube bundle (as illustrated by Fig. 3 for 2 Belgian SG).

The reason for this unexpected evolution is unclear ; whether the "new" cracks were initiated before or after peening is also an unresolved issue.

3.3 Decreasing the environment aggressiveness

An effective way to reduce aggressiveness is to reduce the water temperature. A decrease by 10°C doubles the crack initiation time and T_{hot} reduction has been implemented by a number of American and European plants. However the economical penalty is considerable if the power capacity has to be derated.

Also a leaktight barrier may isolate the susceptible material from the aggressive medium. This can be achieved by electrolytic deposition of a thin (about 0.1 mm) nickel layer on the roll transitions ; this original process was jointly developed by FRAMATOME and LABORELEC. The first field implementations were aiming at the repair of already cracked area (cf. § 6.3 hereafter) but a large scale preventive application was achieved in 1990 on one steam generator of the Doel 2 plant ; 350 tubes, reexpanded above the original roll transition, were preventively nickel plated over the area of high residual stress initiated by the expansion process.

4 FIELD EXPERIENCE

4.1 Problem extent

Despite the large number of SG operating with a large proportion of their tube bundle (up to 60 %) affected by axial EZ-PWSCC, there has been no associated SG tube rupture (SGTR). Also the number of forced outages, because of exceeding the allowable in service leakage, has been quite small even at the time when no systematic RPC inspection was performed.

All of the observed PWSCC has been practically limited to the hot leg side of the tube sheet. This clearly illustrates the dominant influence of temperature (about 30°C difference between cold and hot legs) on the primary water aggressiveness.

As circumferential PWSCC has only been experienced to a limited extent, it will not be further detailed.

4.2 Typical inspection results

The amount and accuracy of available inspection data is much dependent on the various national policies. The best information is of course available from countries allowing SG operation with a large number of TWD cracks, with a distribution of lengths up to the plugging limit. Most of the data are thus coming from Belgium and France who are performing 100 % RPC inspection since 1988 and 1989 respectively.

The following typical results are taken from the Laborelec inspection of the Belgian SG (Doel 2 and 3, Tihange 2 units).

4.2.1 Unpeened rolled transitions

Inspection data from unpeened transitions are scarce, as almost all SG (all over the world) have been peened before implementation of RPC inspection on significantly large tube samples. A unique exception is the Doel 2 plant with part depth rolled SG ; because of the latter feature, no safety concern was raised and consequently no preventive action (such as peening) performed.

After 15 years of operation, 57 % of tubes are cracked in the most affected SG ; their length distribution is illustrated by Fig. 4. The crack growth, monitored on basis of a sample of 565 cracked tubes, has an average value of 0.5 mm/cycle over the length range of 3 to 11 mm.

4.2.2 Peened rolled transitions

A very large and accurate data basis has been accumulated for this case ; it will be illustrated hereafter by the worst affected SG of the Doel 3 unit.

Unlike the preceeding unpeened case, the crack length distribution histogram has an overall bell shape which can be very well approximated by a "gamma distribution" curve (Fig. 5). The average crack growth ranges from less than 1 mm/cycle to slightly more than 2 mm/cycle ; such variations may be observed from plant to plant, but also from SG to SG (for a same plant) or even from cycle to cycle (for a same SG). This crack growth shows a systematic dependance on the initial crack length ; the shorter the starting length, the larger the length increase (Fig. 6).

With time, the length distribution curves shift towards the range of longer lengths (Fig. 7).

The crack growth distribution curve over 2 cycles can be obtained by a stochastic combination of the growth distributions for each cycle.

4.3 Prediction models

There is presently no reliable physical model of FWSOC propagation in the tube material.

The only degradation prediction models are of a semi-empirical nature, on basis of a thorough statistical analysis of the large inspection data base.

The prediction models for the peened SG (the general case) are aiming at crack propagation ; therefore the expected crack length distributions are defined for one or more successive cycles.

These prediction tools are more meaningful when they are based on a model of crack propagation, taking into account all field observations (such as the dependance on initial length) and achieving data reduction in order to retain but a few empirical parameters ; the requested length distribution curves are then obtained by the appropriate stochastic combinations of the known initial length distribution and length increase distributions. One such approach has been developed by LABORELEC, using only 3 data fitted parameters (ref. 1).

5 PLUGGING POLICY

5.1 General approach

Plugging criteria have been historically initiated in the USA, at a time where secondary side wastage (resulting in uniform tube wall thinning) was the dominant tube corrosion mechanism. Taking into consideration safety margins and allowances for defect growth and inspection inaccuracy, a depth plugging limit of 40 % was arrived at and introduced, as a generic requirement in the Technical Specification of most FWR plants, all over the world.

This situation still holds true, today, with some variations, either in the conservative direction (down to 20 % in Japan) or towards some limited relaxation (50 % range for some US plants).

Now a difficulty arises from the fact that the original criteria do not really make much sense for some of the other corrosion mechanisms (such as

cracking and pitting) that were further experienced by SG, because
• the 40 % criterion is overconservative

• no reliable detection can be achieved for shallow defects.

While no uniform policy has been reached, there is presently a clear trend towards a "Mechanism Specific Defect Management" (MSDM) approach.

For the widespread case of PWSCC in expansion zone, this trend is towards acceptance of TWD cracks subject to a length limitation (i.e. the plugging limit is set on length rather than depth). However, today, the national policies are still widely different.

In Japan, there are no signs of a possible acceptance of TWD cracks, whatever their length.

In the USA, the official licencing position is not much different but the US NRC has at least accepted to consider a formal Industry (Utilities and NSSS vendors, within an international Committee conducted by EPRI) proposal of alternate plugging criteria (ref. 2).

In Europe, Belgium and France are operating safely and reliably their SG with a large amount of TWD cracks ; this policy is presently extending to other european countries.

When moving away from a 40 % depth criterion, 2 new limits need to be taken into consideration

- a structural limit
- a leakage limit.

5.2 Structural limit

This limit is established by taking into account the defect critical size, the regulatory safety margins, the environmental geometry, the inservice growth and the ISI sizing uncertainty.

Countries presently using or proposing a length based limit for TWD defects, are not using a uniform approach to derive the structural limit. The following presentation is taken from Belgium and variations from other countries will be later pointed out.

The Belgian approach is derived from a realistic interpretation of NRC regulatory guide 1.121 (ref. 3).

The allowable value of the measured crack length is taken equal to the lowest of the two following evaluations :

FIRST : best estimate, with safety factor

- the average critical length is divided by the RG 1.121 safety factor, for both the normal and accidental conditions. The lowest resulting value is retained. The allowable length is obtained by deducting the average value of :

- sizing inaccuracy resulting from the inspection method,
- the propagation (in length) of the flaw until the next inspection.

SECOND : most conservative estimate, without safety factor

- the minimal critical length is considered
- the allowable length is obtained by deducting the maximum effect of both sizing inaccuracy and crack propagation rate.

As a simplified comparison with the approach from other countries it can be stated that

- France considers only, with some variations, the second evaluation path (most conservative estimate / no safety factor)
- USA Utilities propose, with some variations, the first evaluation path (nominal conditions estimate / with safety factor).

It is also worthwhile mentioning that, in order to assess the critical size

of TWD axial defects, several experimental programs have been conducted in various countries, with rather large discrepancies in the laboratory results (from 20 to 50 %, according to a recent international comparison). This was clearly resulting from some non representative laboratory testing conditions. A recent verification program conducted by LABORELEC under more representative conditions (no sealing for the test specimens with TWD flaws, made possible by the use of a high pressure, high flowrate testing facility) allowed to identify the reliable data and to remove excessive conservatism (ref. 4).

5.3 Leakage limit

Leakage is a consideration for both Normal Operation (NOP) and for postulated accident conditions.

5.3.1 Normal operation limit

Most plants are presently operating with an inservice leakage limit of 0.35 gpm ($\approx$ 500 gpd $\approx$ 79 l/h) set by the plant Technical Specification.

Even plants operating SG with a very large number of tubes affected by PWSCC experience but small to moderate service leakage, with practically no record of forced outage because of exceeding the allowable leakage value.

In fact the field leakage is considerably lower than predictable, from the known population of cracks, on basis of either theoretical assumptions or laboratory experiments. The most likely explanation is the clogging of the tight PWSCC cracks by primary water impurities (crud and/or precipitates).

This detracts somewhat from the reliability of the Leak Before Break (LBB) approach which has long been advocated by some countries to avoid performance of 100 % RPC inspections. Even reducing the allowed level of inservice leakage (down to 5 l/h for some french plants) cannot restore a level of absolute confidence.

Anyway no specific plugging limit is required to limit NOP leakage.

5.3.2 Accident leakage limit

Another safety related limitation may result from the SG primary to secondary leak rate in case of a postulated large secondary side accident. Because of the larger associated differential pressure, the normal operation leak rate could be considerably increased (mainly through widening of the TWD cracks) and lead to an excessive radioactive release to the plant environment. This consideration may result in more tube repair than dictated by the structural plugging limit.

As it does not appear possible to establish a reliable ratio of accident to service leakage, no extrapolation can be performed from the normal operating conditions.

One possible approach is the use of a probabilistic model to provide a direct assessment of SG leak rate under accident conditions. The methodology consists in a stochastic combination of the statistical distributions assumed for each of the contributing parameters. Some of these distributions (as for mechanical properties, tube geometry, crack sizing uncertainty, ...) are approximated by Gaussian curves while the expected crack length distribution (at the end of the next operation cycle) uses a "crack propagation prediction model".

Such a program has been developed and validated by LABORELEC and is now used in Belgium for parametric studies of accident leak rates as an input to the further safety analyses of radioactive release to the environment

(ref. 5).

6 DISPOSAL OF DEFECTIVE TUBES

Defective tubes, i.e. tubes with defects in excess of the plugging limit are disposed of either by removing them from service (plugging) or by repairing them. The objective of repair methods is to reconstitute a resistant and/or leak tight barrier across the cracked roll transition area.

6.1 Plugging

Plugs are installed in both tube ends by various expansion techniques, which unavoidably introduce high residual stress fields in the plugs. First generation plugs were often made from Inconel 600 TT ; a large number of them are now observed to fail by PWSCC and large scale replacement (by Inconel 690 TT) is presently contemplated. Plugs are often of the "removal" type, thus allowing further recovering of SG thermal exchange surface, through unplugging and sleeving.

6.2 Repair techniques with structural capability

All these techniques are basically using an interval sleeve, of corrosion resistant material (Inconel 690 TT), attached to the original tube both above and beneath the degraded section, by using a variety of methods

- mechanical expansion
- brazing
- welding by TIG or laser techniques.

The most critical part of a sleeve repair assembly is the original tube section just above the upper end attachment, because of the key combination of the 3 unfavorable factors (unchanged medium aggressiveness, unchanged material susceptibility and new field of residual stresses).

For long lasting repairs the upper end residual stress field must be either reduced or isolated from the primary water. This can be done

- for welding, by a local stress relieving heat treatment
  - for mechanical expansion, by a prior nickel plating of the original tube.
- When properly carried out, sleeving provides an excellent repair method which, within the present technological state of art, presents nevertheless two significant shortcomings

- poor inspectability of the upper end attachment,
- poor repair accessibility to higher elevations, should it be required by other tube corrosion problems (such as ODS-CC at the support plates levels).

6.3 Repair techniques without structural capability

The only such technique presently available is nickel plating. It is considered as a repair technique when the nickel layer is applied across an already cracked section, thus restoring leaktightness in the case of already TWD cracks.

The thin (typically 0.1 mm thick) nickel layer has no significant structural strength ; thus the method is only applicable to tubes with an acceptable residual strength, i.e. not having reached yet a plugging limit.

Most of the field applications have been achieved in Belgium, on Doel 2 (part depth rolled SG) since 1985 and Doel 3 (full depth rolled SG) since 1988. For the latter case, a key consideration was the verification that the PWSCC, beneath the nickel layer would indeed no more propagate in length

(despite contact with the secondary AVT environment for the TWD cracks).

While ECT examination through the nickel magnetic barrier is not possible, a very sensitive and accurate UT inspection method (cf. § 2.3.1) was applied at the time of plating and during the two consecutive outages (1989 and 1990) ; no propagation was observed, thus providing the last qualification step of the method.

When compared to the sleeving techniques, nickel plating (or "kiss sleeving") has none of the major sleeve limitations (cf. § 6.2), but has a narrower field of application because of its lack of structural strength.

7 AN EXAMPLE OF PWSCC PROBLEM MANAGEMENT

As for other SG problems, roll transition PWSCC has usually been addressed by a general management approach involving some or all the following successive steps :

- Problem detection and characterization
- Dedicated sample monitoring
- Implementation of preventive methods
- Development of specific plugging criteria
- Dedicated 100 % inspection
- Implementation of repair methods
- Adjusted sample monitoring
- Repair versus replacement strategy.

These various steps are reviewed in table 1 for the particular case of the Belgian plant of Doel 3 for which the replacement of SG was recently decided. From the detection of the problem up to completion of the replacement operation, all steps will have taken place in an overall time span of 10 years.

8 CONCLUSIONS

PWSCC in tube roll transitions is undoubtedly a very significant problem both because it affects a large number of SG all over the world and because it may lead to the ultimate decision of SG replacement.

To face efficiently the PWSCC problem it is essential

- to develop a good knowledge of the problems status. This requires a sensitive, accurate and efficient inspection method ;
- to use a Mechanism Specific Defect Management evaluation, properly addressing the actual safety and reliability concerns ;
- to identify the repair techniques by taking into account the longer term possible consequences ;
- to integrate all aspects into a well coordinated overall problem management approach.

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Processing Steps	Year	Methodology / conclusion
Problem detection and characterization	1983	RPC (prototype) PWSCC
Dedicated Sample Monitoring	1984 → 1987	RPC (improved)
Preventive Methods { development { implementation	1984 1985	Heat treatment / Peening Shot Peening (Framatome)
Specific Plugging Criteria		
Structural { development { implementation	(1980) 1987 1988	R.G. 1.121 (+ interpretation) 14 mm plugging limit (RT)
Accident Leakage	1989 →	Probabilistic (LABOLEAK program)
Dedicated 100 % Inspection	1988 →	RPC (optimized) ; 2 days/SG
Repair Methods { development { implementation	1984 → 1987 1988	Nickel Plating (Kiss-Sleeving) Laser Sleeves (W) + Nickel (F)
Adjusted Sample Monitoring	1989 →	100 % RPC + UT (repairs)
Repair / Replacement Strategy	1987 - 1988 1989 - 1990 1990 1993	Prediction model SG degradation Technico-economical assessment Replacement decision Replacement schedule